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The program objective was to study turbulence in the atmospheric boundary layer and to improve our ability to represent that turbulence through simple models useful in applications. Toward that end we carried out observational studies at our Rock Springs field site and theoretical and computational studies using direct and large-eddy simulation. Over the duration of the project we published 22 papers on the topic in scientific journals, have four more under review, made 35 technical presentations at scientific conferences, and supervised the theses of four graduate students. Highlights of the program follow.

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MEASUREMENT, ANALYSIS AND PREDICTION OF ATMOSPHERIC BOUNDARY LAYER TURBULENCE

Final Report

by
John C. Wyngaard, James G. Brasseur, Dennis W. Thomson

September 25, 1998

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URI PROGRAM: MEASUREMENT, ANALYSIS, AND PREDICTION OF ATMOSPHERIC BOUNDARY LAYER TURBULENCE

The program objective was to study turbulence in the atmospheric boundary layer and to improve our ability to represent that turbulence through simple models useful in applications. Toward that end we carried out observational studies at our Rock Springs field site and theoretical and computational studies using direct and large-eddy simulation. Over the duration of the project we published 22 papers on the topic in scientific journals, have four more under review, made 35 technical presentations at scientific conferences, and supervised the theses of four graduate students. Highlights of the program follow.

Refractive-index structure-function parameters

Modern views of wave propagation through turbulence with substantial intermittency, such as that found in the high Reynolds number flows in geophysics, suggest that the refractive index structure-function parameter be reinterpreted as a local flow variable rather than the traditional ensemble average. In our paper on local structure-function parameters (Peltier et al., 1996) we introduced a set of local structure-function parameters that depend on local values of the molecular destruction rates of velocity and scalar variances. These local parameters stem directly from the refined (K62) Kolmogorov similarity hypothesis discussed by Wang et al. (1996). The main focus of the Peltier et al. (1996) paper is the prediction of the local structure-function parameters from large-eddy simulation (LES).

We used these local structure-function parameters to enhance the instantaneous refractive-index profiles obtained from LES in order to make them useful in applications to signal propagation. Typical LES provides instantaneous vertical profiles with a spatial resolution of roughly 15 meters. However, the finer-scale structure of turbulence can play a significant role in EM and acoustic propagation; one often needs instantaneous profiles with resolution on the order of one meter. We have developed a technique that uses the 1962 Kolmogorov hypothesis and our local structure-function parameters to supplement the LES profiles of refractive index with turbulent fine structure on scales down to one meter. We are currently using these local parameters to generate refractive index fields for em propagation calculations based on the parabolic-equation model (Khanna et al., 1998). The results are extremely promising.

Turbulence spectra in the surface layer

In working with LES there is a continuing need for knowledge of the variances of the resolvable and subgrid-scale fields and their dependence on grid-mesh size, distance from the surface, and boundary-layer depth. Such information was vital for the development of the "dynamic drag law" of Wyngaard, Peltier, and Khanna (1998).

In "Spectra in the Surface Layer", (Peltier et al. 1995) we propose new models for wavenumber spectra of turbulence in the atmospheric surface layer. They depart from traditional models in two fundamental ways. First, we model two-dimensional rather than one-dimensional spectra, so our models can be used to scale two-dimensional LES fields. Second, we account for the effects of the large, boundary-layer-scale eddies on the turbulence in the surface layer. In so doing we directly admit the deviations from Monin-Obukhov similarity of the horizontal wind field that are so important in the convective surface layer. Our predicted spectra agree well with observations.

A "dynamic drag law"

The fine-mesh numerical codes used in small-scale meteorology, e.g., LES codes for the atmospheric boundary layer, typically need lower boundary conditions on surface fluxes of momentum, temperature, and water vapor. If the code is based on spatial rather than ensemble averaging, these surface fluxes are random variables; in principle they vary from time step to time step and from grid square to grid square. Current LES codes invariably use surface-exchange coefficients to relate these surface fluxes to differences in velocity, temperature, and water vapor between the surface and the first grid point above. Exchange coefficients relating ensemble-average fluxes to differences in ensemble-average properties under horizontally homogeneous conditions have been reliably established through several decades of surface-layer research. By contrast, very little is known about the exchange coefficients that relate the local, random surface fluxes—those averaged over limited time and space intervals—to local flow properties.

Using scaling relations developed from our spectral work (Peltier et al., 1995) we derived, scaled, and simplified a conservation-equation-based "dynamic drag law" for use in LES (Wyngaard et al., 1998). Its optimum use in LES will require a substantially improved subgrid-scale model in the surface layer, as discussed in the next section.

Analysis of SGS dynamics in the surface layer

As just mentioned, better lower boundary conditions must be coupled with a better subgrid-scale (SGS) model. It is well known, for example, that mean shear is overpredicted at the first few grid levels adjacent to the ground when a variant of the Smagorinsky closure introduced by Deardorff is used. The Ph.D. research of Samir Khanna has shown that this overprediction is much more sensitive to the subgrid-scale (SGS) closure than to refinements in grid resolution. The errors introduced near the ground in the prediction of resolved velocity and temperature fields are driven upward by the buoyancy force, thus infecting the predicted structure of the entire ABL (Khanna and Brasseur, 1998).

The vertical velocity w near the surface is poorly resolved in LES, a consequence of the linear dependence on height of the horizontal integral scale of w. Brasseur et al. (1996) have analyzed the consequences of this underresolution on SGS energetics and dynamics. Through a spectral analysis of direct numerical simulations of resolved–subgrid-scale couplings in isotropic turbulence, they found that when the turbulence is well resolved, as in the mixed layer, the SGS stress model drains energy from the resolved scales correctly in an average sense, but that the modeled subgrid terms in the filtered

Navier-Stokes equation only play a minor role in the evolution of the resolved velocity field. With underresolution the SGS terms dominate and the SGS model must capture correctly not only mean energy flux from the resolved scales, but also important statistical characteristics of the SGS stress-divergence and pressure-gradient terms in the evolution equation for resolved velocity.

With this knowledge, Anurag Juneja has studied the specific errors in SGS dynamics causing the incorrect predictions of mean shear near the surface. Recognizing that underresolution of vertical velocity at the first few grid levels very likely underlies the poor performance of the SGS closures, and noting that the near-surface turbulence is strongly anisotropic and inhomogeneous, we carried out two related studies. First, to eliminate the direct influence of the surface and surface boundary conditions and focus directly on consequences of underresolution in a strongly anisotropic turbulence, Dr. Junega developed two direct numerical simulations (DNS) of anisotropic homogeneous turbulence with very different large scale structure representative of surface-layer turbulence, shear-driven and buoyancy-driven turbulence. Second, to study the direct influence of the surface and large-eddy sweeping on the subgrid contributions to the evolution equations, we analyzed back-filtered, ultra-high-resolution LES of the surface layer.

We find that the overprediction of mean shear in the surface layer can be largely explained by error in the structure of SGS stress divergence and underprediction of the SGS pressure gradient. We discovered a feedback loop between modeled SGS stress divergence and time evolution of resolved velocity that leads, over time, to spurious enhancement of resolved velocity in directions with strongest velocity variance. As a result, the streamwise component of resolved velocity is enhanced near the ground in LES of the ABL, enhancing mean shear. Subsequent analysis of high-resolution LES of the ABL has verified that the same spurious dynamics found in the DNS of anisotropic turbulence may also be found in the ABL, indicating that the combination of underresolution and strong anisotropy near the surface accounts for much of the error in the simulations. The direct influence of the surface, we find, enhances the contribution from the pressure gradient term in the dynamic equation, and magnifies the influence of the pressure boundary condition.

Improvement of LES in the surface layer

Along with the analysis and improvement of the exchange-coefficient boundary conditions (Wyngaard et al., 1998) we have focused on improved prediction of surface layer structure and dynamics by introduction of a "refined mesh" adjacent to the surface, and more recently the development of an SGS paramerization designed specifically for LES at grid cells adjacent to the ground. The refined mesh methodology, using "one-way communication," was developed by Samir Khanna as part of his Ph.D. research (Khanna and Brasseur, 1997). This technology allows for increased resolution of the energy-containing eddies near the ground. From the analyses of Juneja we conclude that to improve predictions near the ground SGS closures must (1) correct a spurious coupling in anisotropic structure between SGS stress divergence and resolved velocity and (2) have the flexibility to capture both RS-SGS energy flux and SGS dynamics (stress divergence) when the integral scales are strongly anisotropic and underresolved. We are exploring the development of a new class of closures whereby the SGS stress is formed from a surrogate subgrid velocity which evolves from an approximate dynamical equation. Initial analysis of this model in homogeneous buoyancy-driven turbulence is very encouraging.

Measurement of resolvable and subgrid-scale variables

In his M.S. thesis research, graduate student Rob Edsall did the first studies of a new measurement technique that uses filtered, differentially weighted time series from several sensors, arrayed laterally to the mean flow, to provide information about turbulent structure at the scales resolvable by LES. Time filtering emulates streamwise spatial filtering, and differential weighting of signals from sensors spaced laterally emulates lateral spatial filtering. Thus, the resulting time series is a surrogate for the time series of the resolvable-scale field measured at that point, and the difference between the unfiltered signal at that point and this "resolvable-scale" signal is a surrogate for the subgrid-scale signal.

Tong et al. (1998) describe the full implementation of the new array technique, including what we believe are the first measurements of time series of the subgrid-scale momentum flux in a turbulent flow.

Surface-layer eddy structure

We studied the two-point coherence of velocity and temperature fluctuations, the effect of Taylor's hypothesis on measurements, and the (fourth-order) spectra of heat flux and stress fluctuations in the surface layer both analytically and experimentally (Tong and Wyngaard, 1995). We made the measurements at our Rock Springs field site with two sonic anemometers separated laterally at a height of 10 m.

These studies are aimed at understanding turbulent eddy structure, especially that contributing most to the heat flux and stress. The results are also important for our resolvable-scale field measurements (Tong et al., 1998).

The one-dimensional coherence for both velocity and scalar fluctuations rolled off at wavenumbers much smaller (i.e., at streamwise scales much larger) than one would expect from the classical notion of eddy correlation. For example, the coherence for the streamwise velocity component begins to fall at a streamwise scale 10 times the sensor separation. Physically, this falloff is a consequence of the cancellation of Fourier components aliased from the direction of the sensor separation into the streamwise direction. The coherence behaves differently for each of the three velocity components, due to the different relative orientations of the velocity component, the sensor separation, and the mean velocity. Our theory captures this behavior very well. We also calculated the two-point scalar-vertical velocity cospectrum with an extension of the theory and the results agree well with our experimental data.

In order to aid our interpretation of such turbulence measurements, we made a formal analysis of the standard use of Taylor's hypothesis (i.e., the frozen-field approximation) to convert two-point time coherence to two-point, one-dimensional spatial coherence at high wavenumbers (Tong, 1996). Both Lumley's two-term approximation and the Gaussian approximation of Wyngaard and Clifford are used in our analysis, which is based on Lumley's idea of a slightly fluctuating convection velocity. In general, we find that the coherences for both streamwise and cross-stream separations are significantly overestimated through Taylor's hypothesis, with the error increasing with wavenumber. Our study suggests that reliable measurement of the two-point spatial coherence can be achieved only for scales not too small compared to the sensor separation.

An important but previously unanswered question in micrometeorology is: how well do flux traces measured by two spatially separated sensors track each other? The theory we developed to answer this question (Tong, 1997) involves fourth-order flux spectra that integrate to the variances of stress and heat flux. We used the quasi-Gaussian approximation to predict the two-dimensional form of these fourth-order spectra. The calculated spectra are in good agreement with our experimental results.

Local structure of the ABL from large-eddy simulation

The three-dimensional local structure and dynamics of the ABL have been analyzed using large-eddy simulation (Khanna and Brasseur, 1998). The stability state was varied from near-neutral to highly convective, and the local structure in velocity and potential temperature was analyzed through spectra and conditional probability density functions. We put forth an argument for the formation of large-scale rollers in moderately convective stability states whereby the local shear-induced streaks in fluctuating streamwise velocity act as seeds for the buoyancy-generated motions throughout the boundary layer.

M.S. student J. Kotter used large-eddy simulation to study the downward dispersion of a passive scalar through the capping inversion. He found that the smaller-scale vortical eddies at the edges of buoyancy-driven large-scale eddies rapidly mix the scalar and effectively guide the time evolution of the highest concentrations of scalar. Whereas the downward motions in the ABL drive the scalar towards the ground, temporal changes in eddy structure can alter the history of dispersion in unexpected ways.

Acoustic scattering

Classical scattering theory predicts that the intensity of a saturated, scattered acoustic signal will have an exponential probability density function (pdf). However, the classical theory does not account for intermittency of the turbulence, which causes quantities such as the scattering cross section to vary in space and time. The classical scattering theory can be modified to include intermittency by making the strength of the turbulence (i.e., the dissipation rate of turbulent kinetic energy) a local property of the scattering volume, as suggested by Kolmogorov in 1962.

We compared the predictions of the intermittency-based theory to measured pdf's obtained for scattering into an outdoor, ground-based, acoustic shadow zone (Wilson et al., 1996). The data clearly show deviations from the exponential pdf, and are predicted well by the intermittency theory. Intermittency dramatically increases the probability of measuring large values of the scattered intensity.

Turbulence dynamics and small-scale structure

Atmospheric turbulence has extremely high Reynolds numbers and therefore has an extremely wide range of length and time scales. In the course of this program several issues of fundamental importance to our understanding of turbulence physics and structure were analyzed.

The classical theories of high Reynolds number turbulence are based on an equilibrium state whereby the energy cascade carries information from the largest to the smallest turbulent scales via local scale interactions. We analyzed several aspects of nonequilibrium scale interactions in high Reynolds number turbulence using direct numerical simulation based on semi-analytical analyses of the nonlinear triadic couplings that appear in the Navier-Stokes equation. In particular we studied the direct influence of the large-scale motions on the dissipative motions via long-range scale interactions that bypass the normal cascade. In one study we determined that the phase relationships among structural features at the small scales are strongly and rapidly influenced by changes in large-scale structure. In another study we found that these structural alterations persist even into the equilibrium state, albeit at a level more difficult to detect. The influence of these dynamical process may be significant in chemical kinetics occurring in regions of the atmospheric where rapid changes occur. These studies are currently only pubished in abstract form.

A second series of studies was directed at the 1962 intermittency hypotheses of Kolmogorov and the extent to which small-scale velocity and scalar fluctuations can be characterized by the local scaling proposed by Kolmogorov and extended by Corrsin, Batchelor and others. Wang et al. (1996) describe the extent to which high-resolution DNS data of isotropic turbulence is consistent with the scalings hypothesized by Kolmogorov in 1962, and the scaling exponents were estimated.

Decomposition strategies and the spectral description

The Ph.D. thesis of Charles Carrano focused on alternative decomposition strategies for high Reynolds number turbulence, which is highly intermittent at the small scales. A numerical algorithm was developed whereby nonlinear dynamical systems can be advanced in time on arbitrary bases. The algorithm was designed to provide a "test-bed" from which alternative bases of arbitrary design can be studied. The method was applied to the one-dimensional Burgers system, the dynamics and structure of which was studied using a basis established from exact solutions to the single shock "Fay" solution for periodic boundary conditions. Further analysis was carried out using wavelet bases to describe the local dynamics of scale interactions from a physical-space perspective.

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- Carrano, Charles S., Ph. D. in Aerospace Engineering, 1997. Thesis title: General Decompositions and Spectral Dynamics Applied to Burgers' Model of Turbulence. J. Brasseur, thesis advisor.

- Cotter, John J., M.S. in Mechanical Engineering, 1997. Thesis title: Scalar Entrainment through the Capping Inversion of the Atmospheric Boundary Layer. J. Brasseur, thesis advisor.

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